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Development of a Multi-Mission Sizing Methodology Applied to the Common Support Aircraft

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ABSTRACT

A methodology is developed for the rapid quantification and exploration of the design space of a multi-mission vehicle. This method is applied to the Common Support Aircraft, a vehicle with four separate missions, to determine which is most critical to size the vehicle. The Airborne Early Warning mission is shown to be critical for sizing the Common Support Aircraft. Furthermore, the method developed gives a feel for the excess capability of the aircraft in its other support roles. Finally, this methodology is shown to be useful in the creation of balanced requirements for multi-mission vehicles.

INTRODUCTION

Today's aircraft are tasked with a wider variety of missions than ever before. Older vehicles are often retrofitted to perform different missions while new vehicles are designed to be capable of multiple roles. The concept of "thoroughbred" aircraft – aircraft designed for superiority in only one role – is becoming obsolete.

It is conceptually impossible to design an aircraft that is a "thoroughbred" for more than one mission, so multi-mission aircraft are inherently compromised to some degree. The typical approach to multi-mission sizing involves sizing a vehicle for one mission (often called the design or primary mission) and determining the performance of the vehicle in the other missions (called the secondary missions). Determining the sizing mission from a collection of mission specifications is the focus of this paper.

BACKGROUND – The primary mission of the United States Navy is to rapidly project power wherever necessary. The Navy does this primarily through its carrier battle groups, a congregation of ships centered around one massive vehicle: the aircraft carrier. This behemoth is a city in itself, a floating airport with over 5,000 personnel stationed on board to care for the vessel and its complement of aircraft. These aircraft are the carrier battle group's tool of choice for projecting power. They are capable of engaging an opposing force far beyond the range of surface vessels and are used for both attack and fleet defense. Aircraft can also gather intelligence about the enemy without giving away the carrier's position.

Space on aircraft carriers is at a premium, massive as they are. Current carriers have a capacity for approximately 100 aircraft. The type of aircraft must be mixed to provide the carrier battle group with capability in all mission areas, which include attack, defense, intelligence, and logistics. Unfortunately, every distinct airframe brought aboard the carrier requires specialized support equipment, personnel, and parts. Therefore, consolidation of multiple missions into one airframe is key for maximum flexibility of the carrier air wing.

The United States Navy currently uses four aircraft in what are considered support roles. These are the E-2C Hawkeye for Airborne Early Warning (AEW), the S-3B Viking for Anti-Submarine Warfare/Anti-Surface Warfare (ASW/ASUW), the ES-3A Shadow for Electronic Surveillance (ES), and the C-2A Greyhound for Carrier On-board Delivery (COD). These four aircraft originated from two basic airframes, so some spare parts and support equipment can be used interchangeably between the E-2C and C-2A, as well as between the S-3B and ES-3A. Each of these aircraft are nearing the end of their service life, so a new support vehicle that can accomplish all support missions is required. This vehicle is the Common Support Aircraft (CSA), an aircraft envisioned to replace these four legacy aircraft with a single airframe and as few variants as possible. It should perform all four support missions to maximize *affordability*, defined as a measure of performance weighed against relative cost.

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GOAL – The following study investigates a rapid method for the creation of a design mission from multiple mission requirements for the CSA. It represents a portion of Georgia Tech's response to a Request for Proposal (RFP) from the 2000/2001 American Institute of Aeronautics and Astronautics (AIAA) Foundation Graduate Team Aircraft Design Competition. This RFP calls for the conceptual design of the Common Support Aircraft with specific mission, vehicle, and data requirements. The full rules for this competition are available in [1].

CSA SPECIFICATIONS AND ARRANGEMENT

MISSION REQUIREMENTS – The missions for the CSA were taken directly from the RFP. There were four missions explicitly defined in this document which reflected the missions of the four support aircraft fielded today – AEW, ASW/ASUW, ES, and COD. All of these requirements were assumed to be inflexible, so the determination of which mission is the most stringent in terms of sizing is paramount in the design of this vehicle. The mission requirements are summarized in Table 1.

CONFIGURATION – Two competing configurations were carried though the entire conceptual design process: a conventional (tail-aft) aircraft with a rotodome atop the fuselage for the AEW sensor requirements and a joined wing aircraft with all sensors integrated into the diamond-like wing planform. The joined wing aircraft appeared to be more promising at the end of the conceptual investigation due to the lower induced drag and reduced weight inherent to the configuration. Furthermore, the placement of the sensors into the wings of the aircraft allowed for system synergy for different support missions. This aircraft is similar to the Boeing EX proposal [2]. The final configuration, dubbed the Gryphon, is depicted in Figure 1.

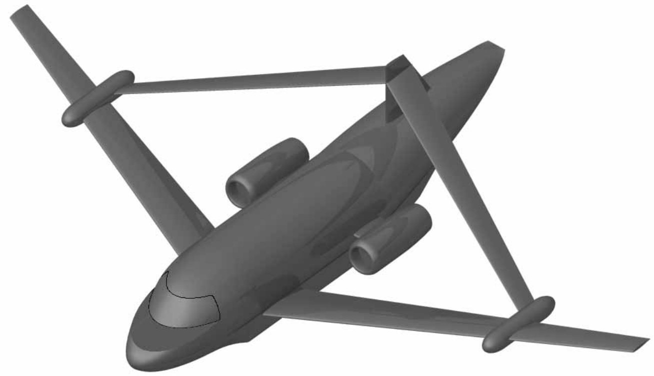

Figure 1: The Gryphon Common Support Aircraft

PAYLOAD REQUIREMENTS – Understanding the payload requirements is paramount in the choice of a sizing mission. The RFP specifies the payload for each mission as outlined in Table 2. However, some of this payload can be common for each mission. The COD mission, requiring the least in terms of mission-specific equipment, has to carry 2,000 pounds of avionics. This represents the basic avionics necessary for the operation of the aircraft, and thus can be assumed to be the same for every mission.

Segment	*AEW*	*ASW/ASUW*	*ES*	*COD*
Warm-up, taxi & takeoff	fuel consumption: 5 min. @ max power	fuel consumption: 5 min. @ max power	fuel consumption: 5 min. @ max power	fuel consumption: 5 min. @ max power
Climb	max climb power to cruise altitude	max climb power to cruise altitude	max climb power to cruise altitude	max climb power to cruise altitude
Cruise	250 nautical miles best alt. and speed	245 nautical miles best alt. and speed	520 nautical miles best alt. and speed	1600 nautical miles best alt. and speed
Loiter	270 min. @ 35,000 ft. best speed	270 min. @ 25,000 ft. best speed	150 min. @ 40,000 ft. best speed	N/A
Weapons release	N/A	anti-ship missiles 2,200 pounds total	N/A	N/A
Return cruise	250 nautical miles best alt. and speed	245 nautical miles best alt. and speed	520 nautical miles best alt. and speed	N/A
Descent	sea level no distance credit	sea level no distance credit	sea level no distance credit	sea level no distance credit
Loiter	20 minutes best speed	20 minutes best speed	20 minutes best speed	20 minutes best speed
Reserve	5% of mission fuel	5% of mission fuel	5% of mission fuel	5% of mission fuel

Table 1: CSA Mission Specifications

Mission Equipment	*AEW*	*ASW/ASUW*	*ES*	*COD*
Avionics and sensors	12,000 pounds includes radar system	5,000 pounds	9,800 pounds	2,000 pounds
Expendable payload	none	5,200 pounds 68 A-size sonobuoys 2 advanced torpedoes 2 advanced anti-ship missiles	none	none
Retained payload	none	none	none	10,000 pounds OR 26 passengers

Table 2: CSA Payload Specifications

An enabling technology for the Gryphon was the judicious use of Monolithic Microwave Integrated Circuits (MMICs). These sensors can simultaneously transmit and receive radio energy at multiple frequencies and wavelengths [3]. This gives the Gryphon the ability to accomplish all of its sensing requirements for the AEW, ASW/ASUW, and ES missions with the same sensors. MMICs are currently used in several systems today, including cell phones. When integrated into a sensing vehicle, multiple MMICs can be used in an Active Electronically Steered Array (AESA). In AEW applications, the AESA array weighs on the order of 2,000 pounds, as seen in the ERIEYE program [4].

Advances in software development could also enable the Gryphon to accomplish the aforementioned missions with the same mission equipment. Unfortunately, this was beyond the scope of the project as specified within the RFP, so each mission was assumed to require specialized mission equipment. However, it was assumed that such equipment could be modular, so the mission-specific payload requirements were interpreted as the difference between the total payload required and the common array weight. Table 3 summarizes the payload requirements for each mission. Note that the 2,000 pounds of common sensor array, beyond the 2,000 pounds of common avionics, appears as a weight penalty for the COD mission, which has no sensor requirements. If the investigation of the mission space proves that the COD mission is the most critical in terms of sizing, then the idea of a completely common airframe for this vehicle may not be the most affordable solution. Also note that the required payload of the COD mission has been decreased by 380 pounds to reflect the need for only two crew members on this mission versus the four for all other missions (the vehicle is sized assuming four crew members).

A detailed investigation of the design of the Gryphon is found in [5], and is available from the AIAA or the authors upon request. For this study, vehicle dimensions are kept constant.

Equipment	*AEW*	*ASW / ASUW*	*ES*	*COD*
Common avionics	2,000 lbs	2,000 lbs	2,000 lbs	2,000 lbs
Common array	2,000 lbs	2,000 lbs	2,000 lbs	2,000 lbs
Remaining payload	8,000 lbs	6,200 lbs	5,800 lbs	9,620 lbs
Total payload	12,000 lbs	10,200 lbs	9,800 lbs	13,620 lbs

Table 3: Gryphon Sensor and Payload Weights

METHODOLOGY

Mission requirements can be thought of as variables within a multi-dimensional mission space. Each mission will have its own variable settings that effect vehicle size, such as range, time on station, and payload. The entire mission space is defined by the range of variable settings each specific mission embodies. For example, the time on station dimension within the mission space of the CSA varies from zero to 270 minutes.

Certain portions of this space represent variable settings that do not satisfy one or more of the mission requirements. For example, setting the loiter time to its lowest setting of zero minutes, the range setting at its lowest of 490 nautical miles, and the payload at 5,800 pounds will intuitively create a vehicle that is not large enough (not enough payload-range capability) for any of the support missions. Therefore, each mission has a surface within the mission space that represents a sizing constraint. Creation of these surfaces requires a tool that can be run rapidly for several points within the design space. Most mission analysis tools are cumbersome in that they require iteration to converge to a single point. A metamodel for vehicle sizing that can be created with a few analysis code runs is useful for the creation of these constraint surfaces and subsequent investigation of the mission space. This can be accomplished through a variety of multivariate regression techniques.

RESPONSE SURFACE METHODOLOGY – Response Surface Methodology, or RSM, is a multivariate regression technique based on Design of Experiments (DoE) methodology. A DoE is an ordered set of experiments design to minimize the number of data points (from the analysis code) needed to provide a multivariate regression polynomial equation while ensuring that these variables are not correlated with each other.

Using RSM, the designer picks any number of responses and creates simple mathematical models for each response that are a function of the design variables. Response Surface Methodology typically uses second-order quadratic equations of the form

$$R = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} b_{ij} x_i x_j \qquad (1)$$

where R is the response, b_0 is an intercept term, b_i are regression coefficients for the first-degree terms, b_{ii} are coefficients for the quadratic terms, b_{ij} are coefficients for the cross-product terms, and x_i is the i^{th} control variable. This regression, known as a Response Surface Equation (RSE) is able to model linear effects through the linear terms, curvature effects through the quadratic terms, interaction effects through the cross-product terms, and effects not related to the control variables through the intercept term. This makes it a robust model for most sophisticated analysis codes, and it can run in a fraction of a second versus the several seconds to hours typical of most analysis tools. A more detailed discussion of RSM is available from [6].

MISSION ANALYSIS – The primary tool used for the creation of the metamodels was FLOPS, a mission analysis code developed by NASA [7]. It uses simple physics-based models and historical regressions to size the vehicle and output mission performance. It is calibrated for subsonic, tail-aft transports but can handle canard and three-surface configurations. FLOPS was adapted to handle the Gryphon's unusual joined wing configuration through input aerodynamics and modified group weight algorithms.

FLOPS was calibrated before proceeding with the mission space investigation to provide more physically meaningful data. No data was available for a carrier-based joined wing sensor platform, so FLOPS was calibrated to the S-3A Viking, an existing conventional carrier-based aircraft. This aircraft was used because it is currently used for two of the four support missions, and reflects the construction the CSA will most likely use (partial use of composites, high-bypass turbofans, etc.). Data for the S-3A was found from [8], [9], [10], and [11]. No data was available for the design mission for this aircraft, so a design mission was constructed from one of its current missions as outlined in [9] and the design load factor modified accordingly.

FLOPS was calibrated by inputting the vehicle's geometric data and comparing the output group weights to the weights given in [10]. FLOPS has a number of "dials" that allow the user to modify the outputs to relect small differences in design, such as an increase in fuselage weight for carrier-based aircraft. The "dial" settings are found through manual iteration of the program until the group weights of the output converged to the published weights. At the end, most of the weights were correct to within a few percent to a fraction of a percent. Table 4 compares the calibrated FLOPS output to the published data.

Component	*Predicted (lbs)*	*Published (lbs)*	*Error (%)*
Wing	4901.0	4890.1	-0.22
Horizontal tail	839.0	828.5	-1.27
Vertical tail	517.0	525.4	1.60
Fuselage	5069.0	5067.9	-0.02
Landing gear	1678.0	1699.9	1.29
Nacelle	805.0	805.2	0.02
Engines	3030.0	2991.2	-1.30
Engine accessories	148.0	147.7	-0.20
Fuel system	346.0	345.8	-0.06
Control system	1688.0	1604.2	-5.22
Auxiliary power unit	255.0	254.6	-0.16
Instruments	174.0	174.2	0.11
Hydraulics	390.0	388.9	-0.28
Electrical	832.0	831.7	-0.04
Avionics	4353.0	4352.7	-0.01
Furnishings & equip.	860.0	860.4	0.05
Air conditioning	782.0	782.3	0.04
Anti-icing	177.0	176.8	-0.11
Empty weight	26844.0	26727.5	-0.44
Takeoff gross weight	49910.9	49997	0.17

Table 4: Calibration of FLOPS Output to S-3A Data

MISSION SPACE EXPLORATION

The creation of the mission space begins with parameterization of the requirements into mission space variables. Referring again to Table 1, it is seen that each support mission can be thought of in terms of a generic model with nine variable segments. These are (1) warm up, taxi, and takeoff, (2) climb, (3) cruise, (4) loiter, (5) weapons release, (6) return cruise, (7) descent, (8) loiter, and (9) landing. Figure 2 depicts this generic support mission model.

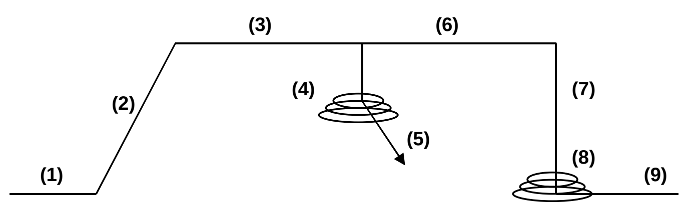

Figure 2: Generic Support Mission Profile

Not all segments vary with the support missions. Inspection of the support requirements shows that the only sections that change are the cruise, first loiter, release, and return cruise segments. If the COD cruise requirement of 1600 nautical miles is broken into two 800 nautical mile segments with no loiter in between, the second 800 nautical mile segment can be considered as a return cruise with this model. In this case, the cruise segment for all missions will equal the return cruise segment. Now the CSA missions can be portrayed with the mission model above using three independent segments (cruise out, first loiter, and release) and differing payloads. An argument can also be made for elimination of the release segment, as the aircraft should be able to land without dropping its weapons in the event that it does not engage any targets or has a release malfunction. This reduces the number of independent segments to two: cruise out and first loiter. The CSA mission space can now be investigated with only four variables: payload, design range (defined as twice the mission radius), loiter altitude, and loiter time on station. The mission space variables and their ranges are given in Table 5.

Variable	*Low*	*High*	*Units*
Payload	5800	9620	
Design range	490	1600	nmi
Loiter altitude	25000	40000	ft
Loiter time	0	270	min

Table 5: Mission Space Variables and Ranges

These variables are placed into a DoE table for analysis. The DoE chosen for this study was a resolution five central composite design with 25 variable settings.

These settings are fed directly into a FLOPS input file. This file is set up to size the vehicle to the generic mission of Figure 2 and other inputs (such as vehicle dimensions) that are not varied. The mission analysis is then rerun for each support mission with the empty weight of the vehicle fixed. As such, FLOPS is only able to vary the fuel weight, as the payload weight and empty weight are fixed. This enables the creation of a "delta weight" response for each support mission, defined as

$$\Delta TOGW = TOGW_{DM} - TOGW_{SM} \tag{2}$$

where $\Delta TOGW$ is the "delta weight" response for a support mission (AEW, ASW/ASUW, ES, or COD), $TOGW_{DM}$ is the takeoff gross weight calculated from the design (sizing) mission, and $TOGW_{SM}$ is the takeoff gross weight calculated for one of the support missions using the empty weight calculated from the design mission. The delta weight response is useful because a negative value indicates an underdesigned vehicle and a positive value indicates an overdesigned vehicle. If all of the mission requirements were perfectly balanced, some combination of mission variable settings would yield four delta weight responses of zero. However, such a case is highly unlikely. This method does allow the designer to see which mission is the most critical and will end up sizing the vehicle.

Next, FLOPS was run at the 25 variable settings within the DoE and the four delta weight responses were tracked for each setting. The DoE and delta weight values were fed into JMP [12], a statistical analysis package, for generation of the four delta weight RSEs.

RESULTS

The delta weight constraint surfaces within the mission space are determined from the RSEs. These constraints may be viewed in multiple dimensions, so the choice of axes must reflect a quantity which the designer can have an intuitive feel for. Therefore, the constraint lines were mapped onto the familiar payload-range diagram. Contours of constant loiter time were mapped onto this diagram for each mission with the delta weight response set to zero. Note that a delta weight of zero for a particular mission indicates that the vehicle is sized to that particular mission. This resulted in four separate plots, one for each mission. A plot for the payload-range of the AEW mission (delta weight AEW set to zero) with each of the support missions mapped onto it is shown in Figure 3.

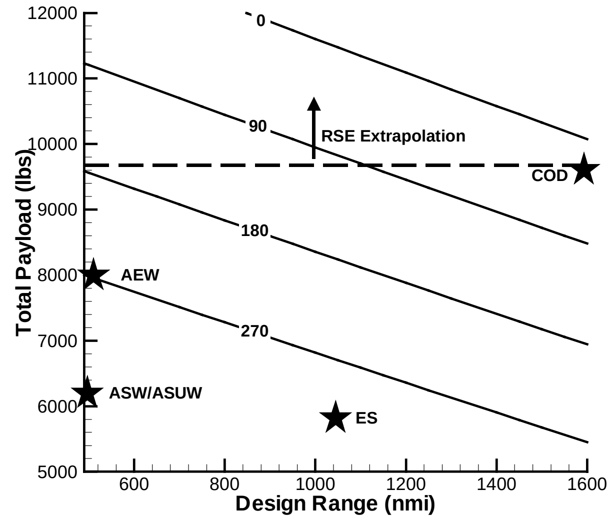

Figure 3: Payload-Range Diagram for AEW Mission

This plot shows definitively that any vehicle sized for the AEW mission will meet or exceed all of the other support mission requirements. Note that the payload dimension goes outside of the range used in the definition of the RSE. Therefore, any payload above 9,620 pounds represents extrapolation of the delta weight RSE. This is normally ill-advised due to the quadratic terms within the RSE; however, the delta weight responses are quite linear, enough so that they can be slightly extrapolated in this case. This simply provides a clearer picture of the mission space, and is not recommended for other purposes.

None of the other missions meet all of the requirements. Figures 4, 5, and 6 depict the payload-range diagram when the delta weight response is set to zero for the ASW/ASUW, ES, and COD missions, respectively.

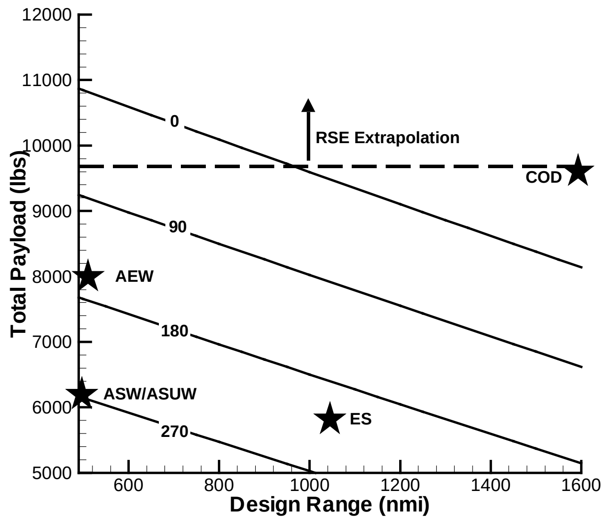

Figure 4: Payload-Range Diagram for ASW/ASUW Mission

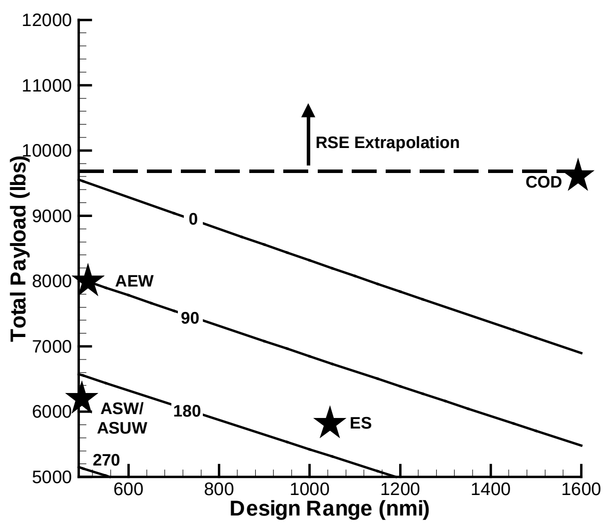

Figure 5: Payload-Range Diagram for ES Mission

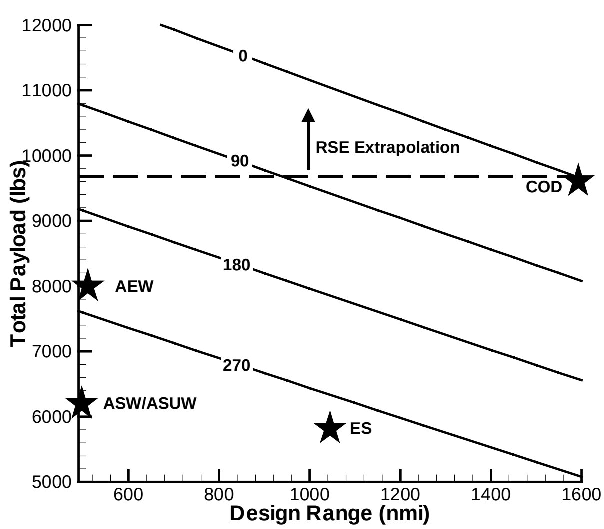

Figure 6: Payload-Range Diagram for COD Mission

IMPLICATIONS

The most obvious implication of this data is the choice of a sizing mission for the CSA. Figures 4 shows that vehicles sized for the ASW/ASUW mission fail both the AEW and COD mission requirements. If sized for the ES mission, the vehicle does not meet all other support mission requirements, as seen in Figure 5. Finally, Figure 6 shows that aircraft sized to the COD mission fails the AEW requirements. Therefore, the CSA is only capable of satisfying all support mission requirements when sized to the AEW mission, as seen in Figure 3. Note that the actual sizing mission need not be the explicit variable settings of the AEW mission, but rather any combination of variable settings that yields a delta weight response of zero for the AEW mission.

This data has other implications as well. While this method works well for choosing a sizing mission, it also indicates how much excess capability is available to the aircraft in the other mission configurations. This information is valuable to the designer at the conceptual level when making decisions regarding issues such as internal fuel capacity and cargo volume. The Gryphon has a fuel capacity 3,000 pounds over its most stringent mission. In this fashion, the Gryphon is capable of maximizing its performance in all support missions (in this case, 3,000 pounds reflected the approximate amount of fuel to bring the ES configuration to maximum TOGW). Figure 7 depicts the radius-loiter capability for the three support missions that require loiter on station. It also shows the capability of the aircraft with zero payload and maximum internal fuel (as might be the case if the Gryphon was to perform an aerial refueling mission).

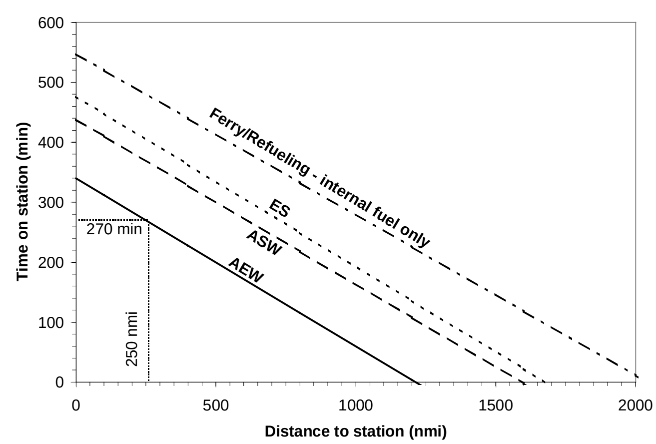

Figure 7: Mission Radius and Loiter Time for Various Support Missions

All of this assumes that the mission requirements are rigid. However, the same method can be used in the determination of mission requirements. In such a fashion, the entities setting the requirements have the ability to create a balanced set of mission requirements. If this is not possible, the agency is at least able to see what effect their requirements have on the vehicle size, and if indeed a multi-mission vehicle is capable of achieving what is required in an affordable fashion.

CONCLUSION

A methodology has been developed for the rapid quantification and exploration of the design space of a multi-mission vehicle. This method has been applied to the Common Support Aircraft and a design mission chosen from a set of support mission requirements. This design mission reflects the Airborne Early Warning support mission specifications. The excess capability of the other support missions has been easily quantified by examining the available mission space of the other support missions. Finally, the method developed within this document can be used by the entities setting the vehicle requirements to create a balanced array of specifications for multi-mission aircraft.

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ACRONYMS

AESA	Active Electronically Steered Array
AEW	Airborne Early Warning
ASDL	Aerospace Systems Design Laboratory
ASW/ASUW	Anti-Submarine / Anti-Surface Warfare
COD	Carrier On-Board Delivery
CSA	Common Support Aircraft
DoE	Design of Experiments
ES	Electronic Surveillance
MMIC	Monolithic Microwave Integrated Circuit
RFP	Request For Proposal
RSE	Response Surface Equation
RSM	Response Surface Methodology
TOGW	Takeoff Gross Weight